Collisionless Shocks
in Gamma Ray Burst Afterglows

Particle Acceleration & Magnetic Field Generation

Christian Hededal   Åke Nordlund
Jacob Trier Frederiksen   Troels Haugbølle

Niels Bohr Institute / Dept. of Astronomy, Copenhagen

Huntsville, Alabama – February 2004

Outline of Talk

- Introduction – GRB backgrund
- Motivation
- Simulations
- Results
- Implications and future goals.

Introduction

We need to understand:

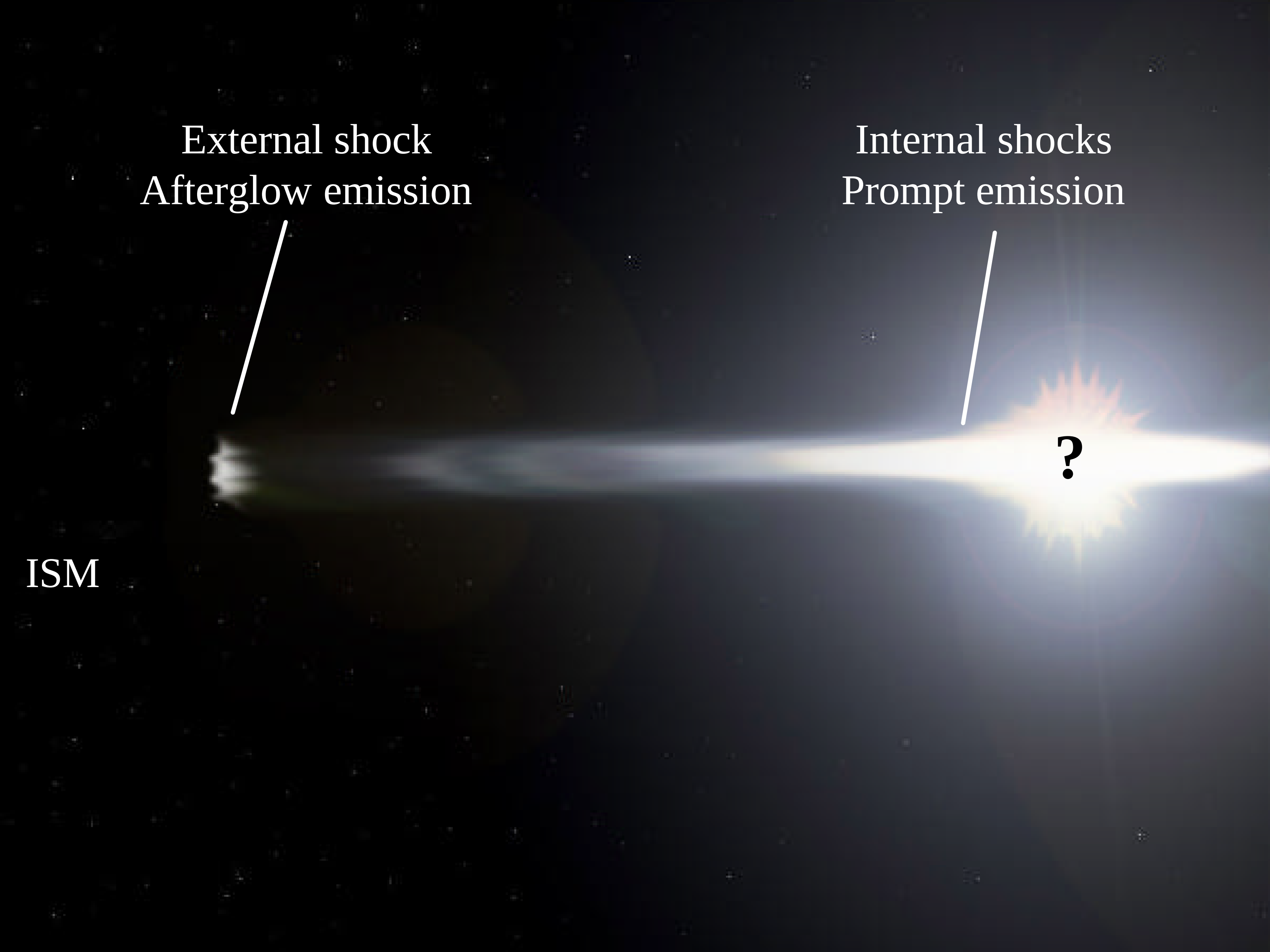
Collisionless plasma shocks

Applicable to

- Supernova shells
- Jets
- Solar wind
- **Gamma Ray Bursts afterglows**

GRB “history”

- First discovered in late 1960s.
- 1991 BATSE launched onboard CGRO.
- 1997 BeppoSax pinpointed afterglow
  (GRB 970228)
- 1999 Evidence of collimation.
  (Kulkarni & Harrison 1999)
- 2003 Supernova found in optic afterglow
  (Galama et al. 1998, Kulkarni et. Al, 1998, Supernova 1998b vs. GRB 980425
  Hjorth et al. 2003, Stanek et al. 2003)



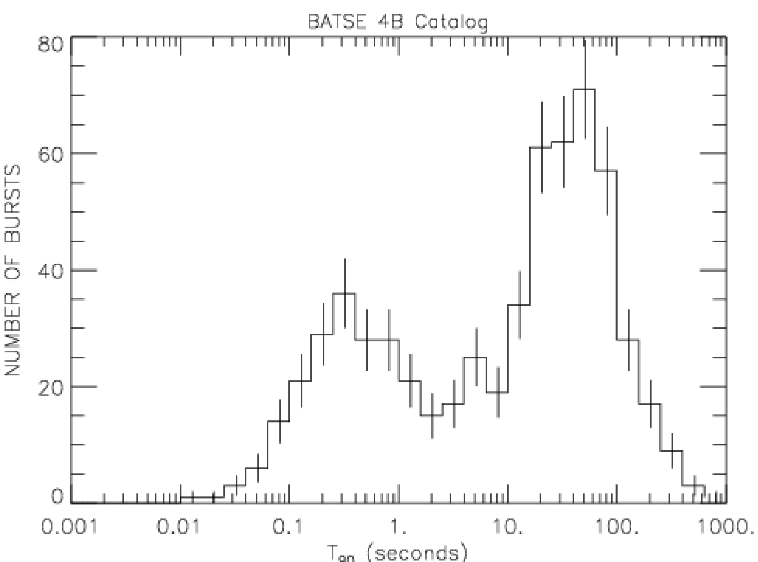
External shock
Afterglow emission
Internal shocks
Prompt emission
?
ISM

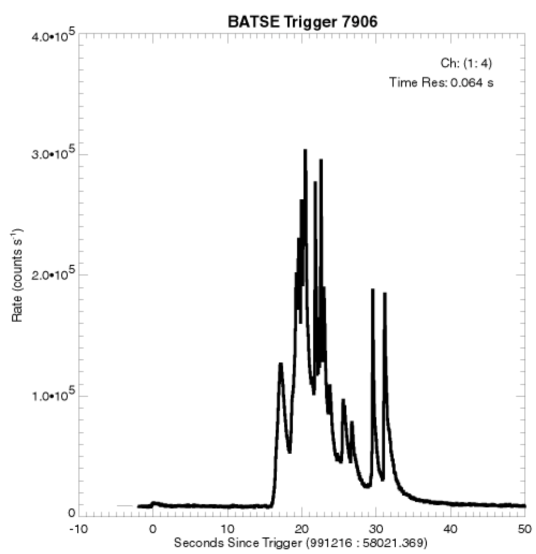
Observational Features

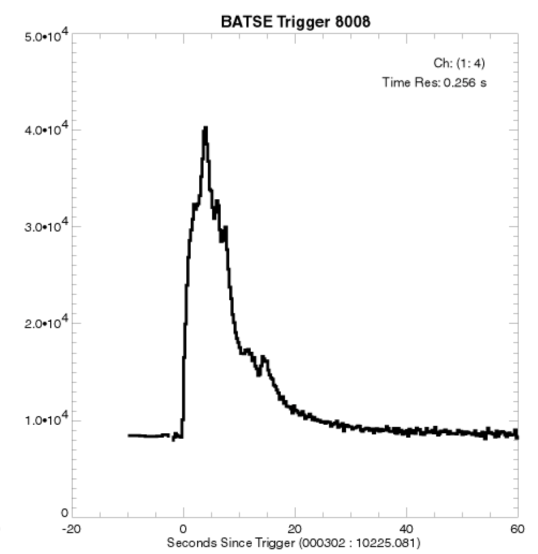
Prompt Emission and the Afterglow

GRB features – Prompt emission

- ~ 0.5 $Myr^{-1} galaxy^{-1}$ (BATSE)
- Duration spans 5 orders of magnitude.
- Pulses are FRED-type lightcurves.
- Non-thermal spectrum (BAND spectrum).







GRB features – Afterglow

- Observed in X-ray, optical/in frared and the radio band.
- Power-laws with variations:

$$F(t,u) \propto t^{a} u^{b}$$

- Some bursts have an achromatic break in temporal decay-slope.
- Most likely synchrotron radiation

The Synchrotron Interpretation

Synchrotron radiation requires:

1. A strong magnetic field
2. Moving particles

Standard fitting procedure:

- Assume homogeneous magnetic field (ε_B)
- Assume particle power-law distribution:

$$N(g) \propto g^{-p}$$

The Synchrotron Interpretation

Observation

Near-equipartition energy in magnetic field e_B

Near-equipartition energy in electrons e_e

Synchrotron radiation

Burst parameters

????

Problems – Magnetic Field

- Can not be compressed $\mathbf{B}_{\mathrm{ISM}}$.

$$\left|\mathrm{B}_{shock}\right| \approx 3\Gamma_{shock}\left|\mathrm{B}_{ISM}\right|_{\perp}$$

- Part of **B** could be carried from engine.

- Normal assumption that ε_{B} homogeous but…

Problems – Particle Acceleration

- … Fermi acceleration needs a turbulent **B**.

- Fermi acceleration theory seems universal:

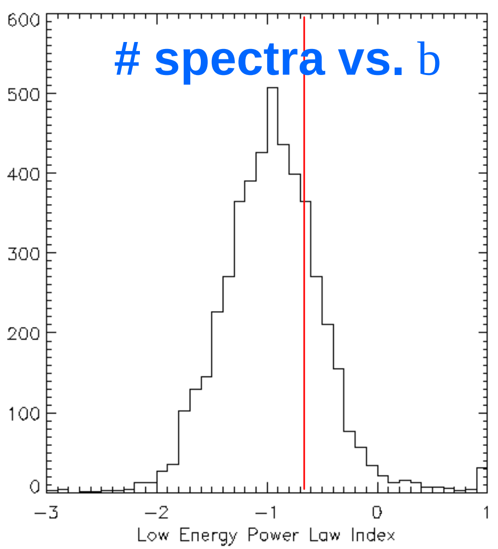
$$N(\gamma) \propto \gamma^{-p} \quad \textbf{where} \;\; p \approx (2.2 - 2.3)$$

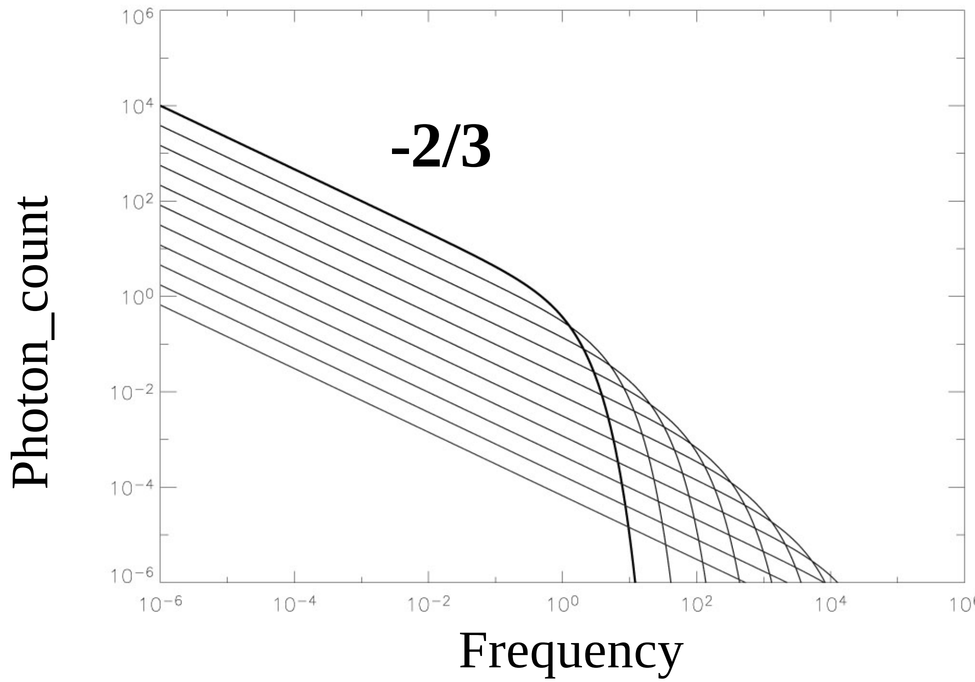
- Afterglow observations yield:

$$N(\gamma) \propto \gamma^{-p} \quad \textbf{where} \;\; p \approx (1.4 - 2.8)$$

Manifestation of the Problems

- Line of death





- We stand with microphysical parameters p, ε_e , ε_B that reflect our lack of knowledge.

We should like to understand…

- Is there a shock mechanism that can create a **magnetic field** strong enough?
- Is **particle acceleration** taking place in the shock – if yes, to which distribution?

THIS PROJECT IS STILL

Theoretical Framework

- ~~Hydrodynamics (HD)?~~
- ~~MagnetoHydrodynamics (MHD)?~~
- Full EM & kinetic treatment

Particle Code

3D Relativistic PIC-code

PIC code original from **Dr. Michael Hesse /GSFC.**

Made relativistic by **Jacob Trier Frederiksen /NBI.**

Particle Code

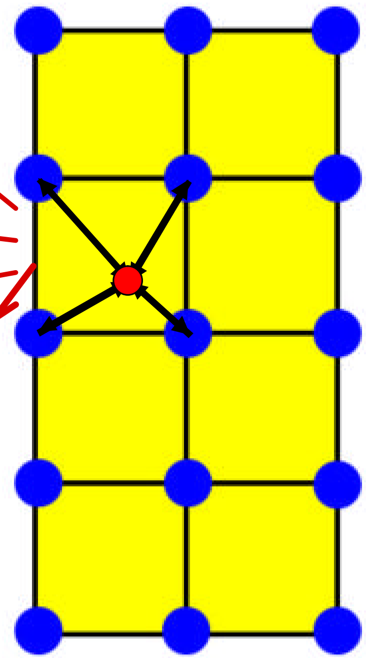
$$\nabla \times \mathbf{B} - \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t} = \mu_0 \mathbf{J}$$

$$\nabla \times \mathbf{E} - \frac{\partial \mathbf{B}}{\partial t} = 0$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

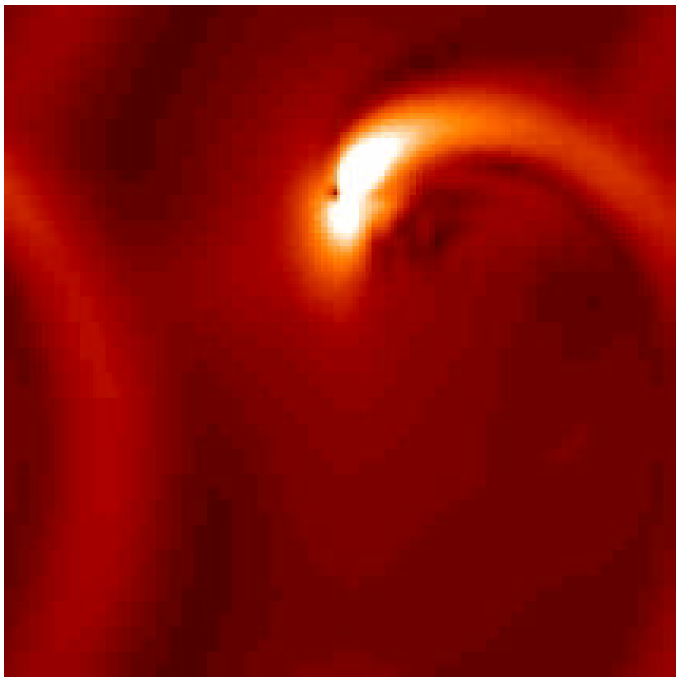
$$\frac{\partial \gamma m \boldsymbol{v}}{\partial t} = q(\mathbf{E} - \boldsymbol{v} \times \mathbf{B})$$



- **B** and **E** staggered in space and time
- 2^{nd} order accuracy in (t,**r**)
- Quadratic spline-interpolation (TSC)

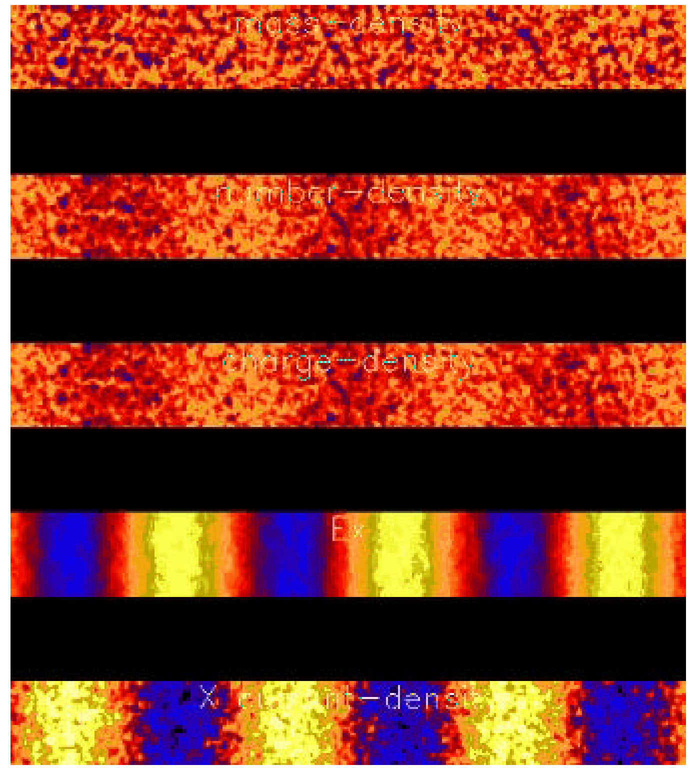
Particle Code (sanity tests)

Single particle motion



J. D. Jackson

Collective motion



Mass density

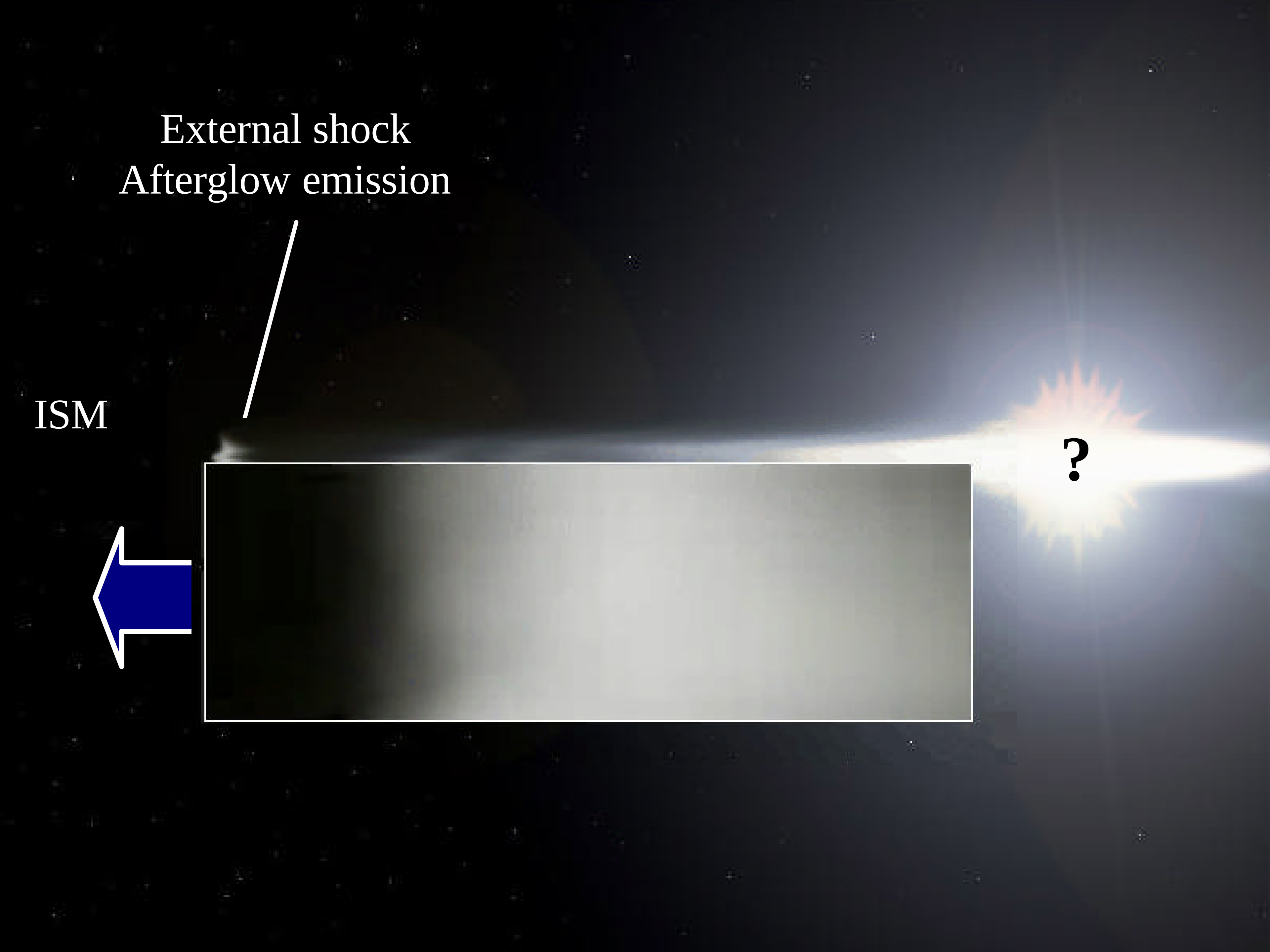
Number density

Charge density

E - field

Current density

The Simulation Setup


External shock
Afterglow emission
ISM
?

The Simulation Setup

200 x 200 x 800 (x 25)

125 x 125 x 2500 (x 25)

~ 10^9 particles (50 GB memory).

Weeks on 8 proc IBM RS6000 with OpenMP

Runs ~ 0.3 Mparticles/s on a Pentium 4 laptop.

Nx = 200

Nz = 800

m_i/m_e	= 16 (8-20),
ω_{pe}	= 0.20,
Γ_{sh}	= 3,
n_{sh}/n_{ISM}	= 3
Particles pr. Cell	= 25 (10-100).
Simulation time	= 2400 = 480 ω_{pe}^{-1}

Boundary Conditions

Along the stream (z): Open (EM-damping)

Transverse (x, y): Periodic.

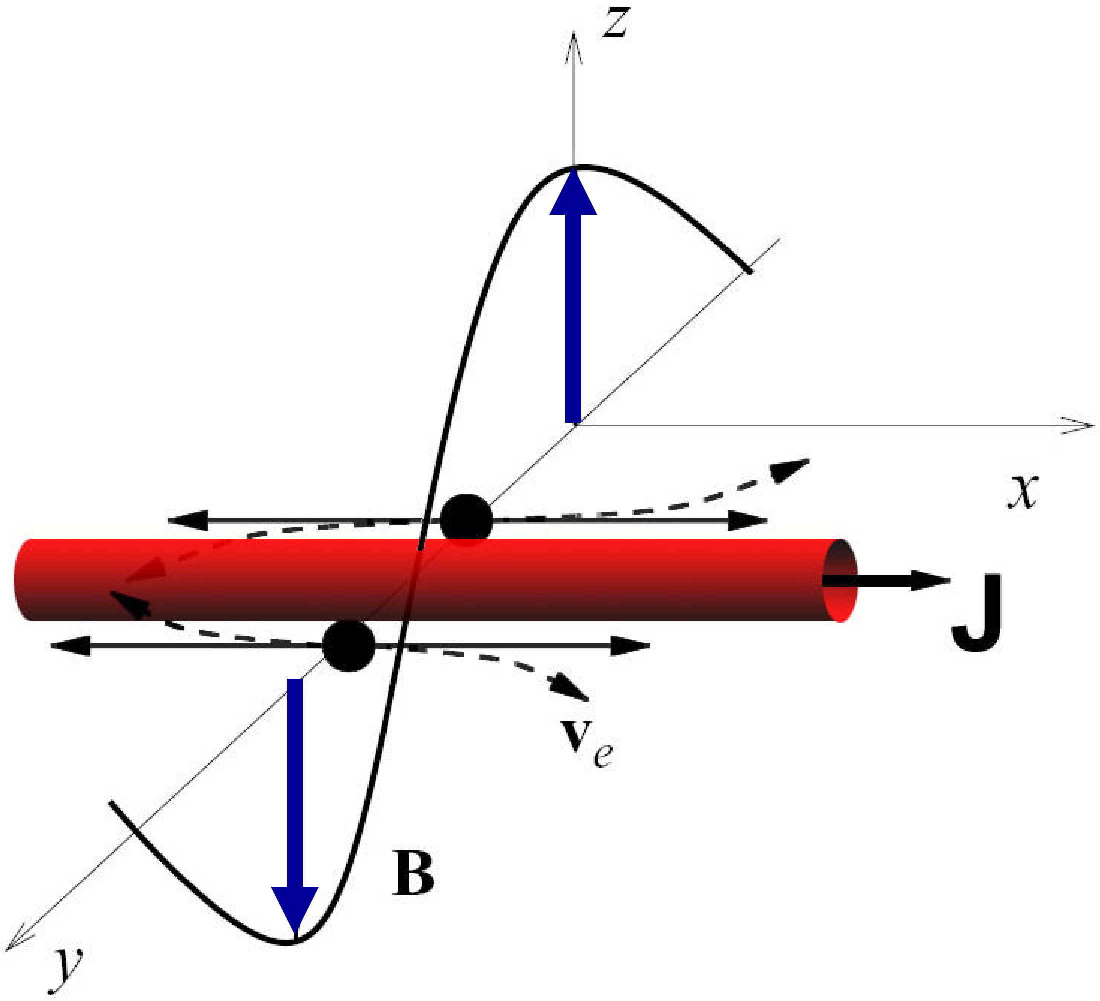
Magnetic Field Generation

The Weibel Instability (two-stream)

Well known and understood

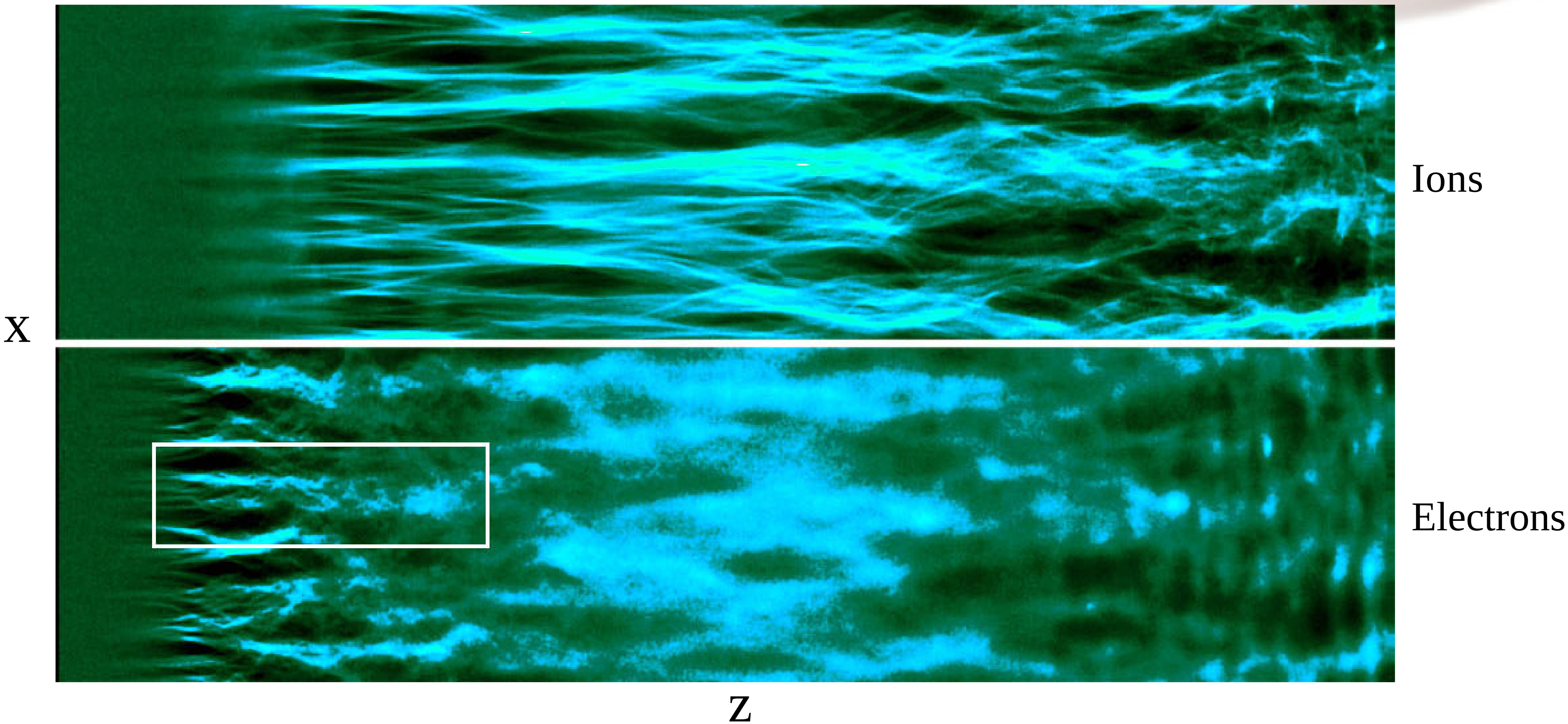
- First principles; anisotropic PDFs
  - Weibel 1959, Fried 1959, Yoon & Davidson 1987
- Numerical studies, electron-positron, 2-D
  - Wallace & Epperlein 1991, Yang et al 1994
  - Kazimura et al 1998 (ApJ)
- Numerical studies, relativistic, ion-electron
  - Califano et al 1997, ‘98, ‘99, ‘00, ‘01, ’02, ..
- Application to GRBs
  - Medvedev & Loeb 1999, Medvedev 2000, ’01, …
- Numerical studies in the GRB framework
  - Frederiksen et al 2003, Nishikawa et al 2003, Silva et al 2003

The Weibel Instability (two-stream)

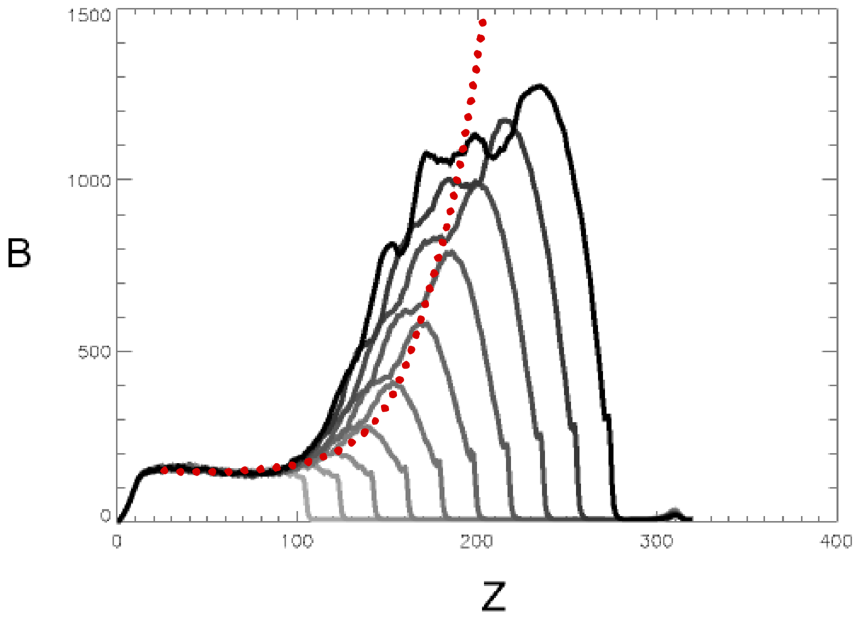


(Weibel 1959, Medvedev & Loeb 1999)

Current Density

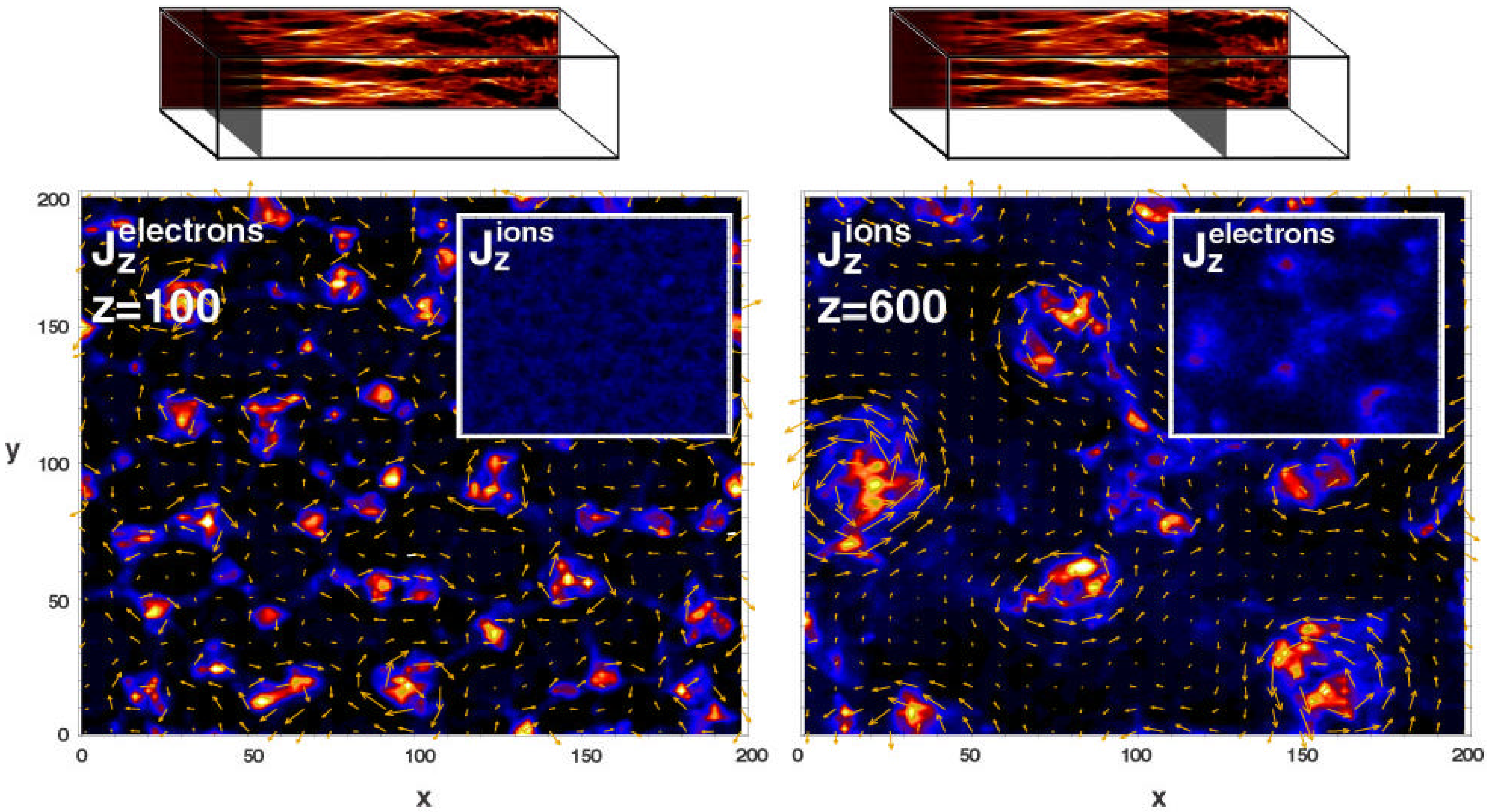


Growth rate (sanity test)

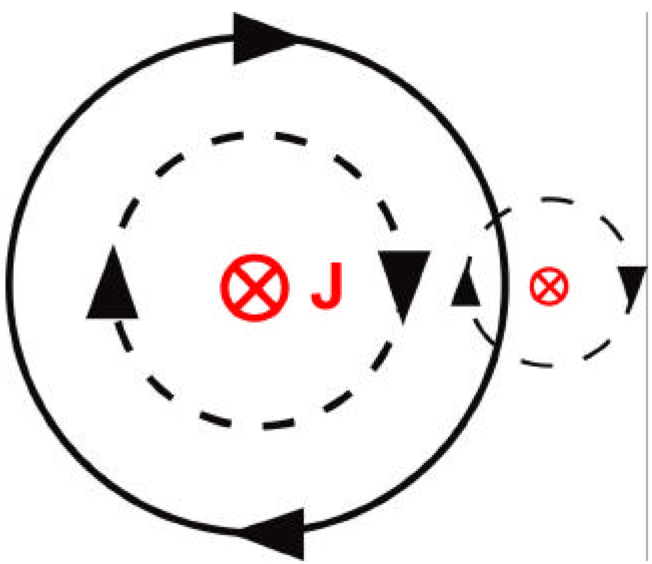


$|\mathbf{B}^2| \propto e^{t/\tau}$ where $\tau = \gamma^{1/2}_{\mathbf{sh}} / \omega_{\mathbf{pe}}$ Medvedev & Loeb 1999

The Two-Stage Process.



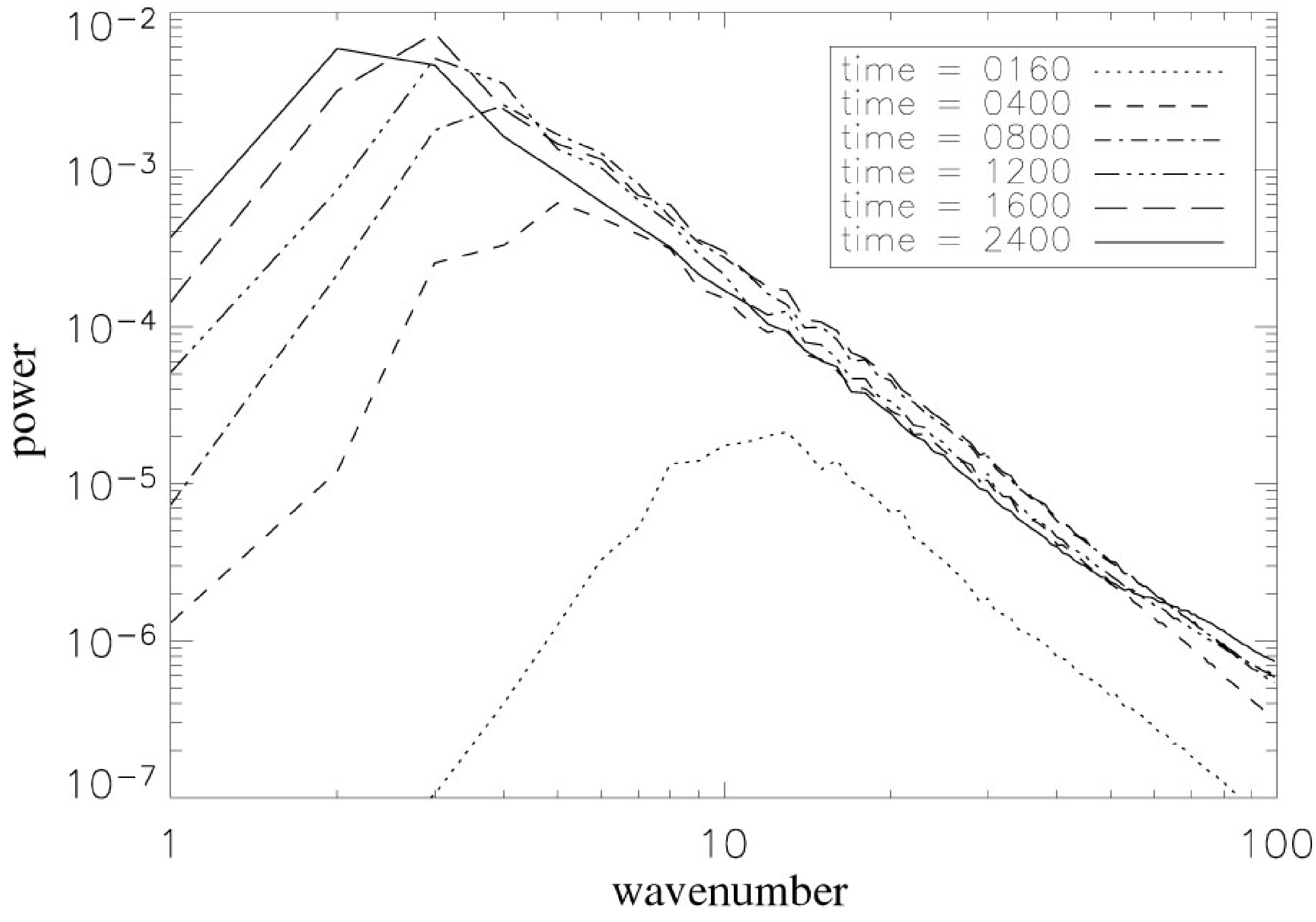
The Non-Linear Stage



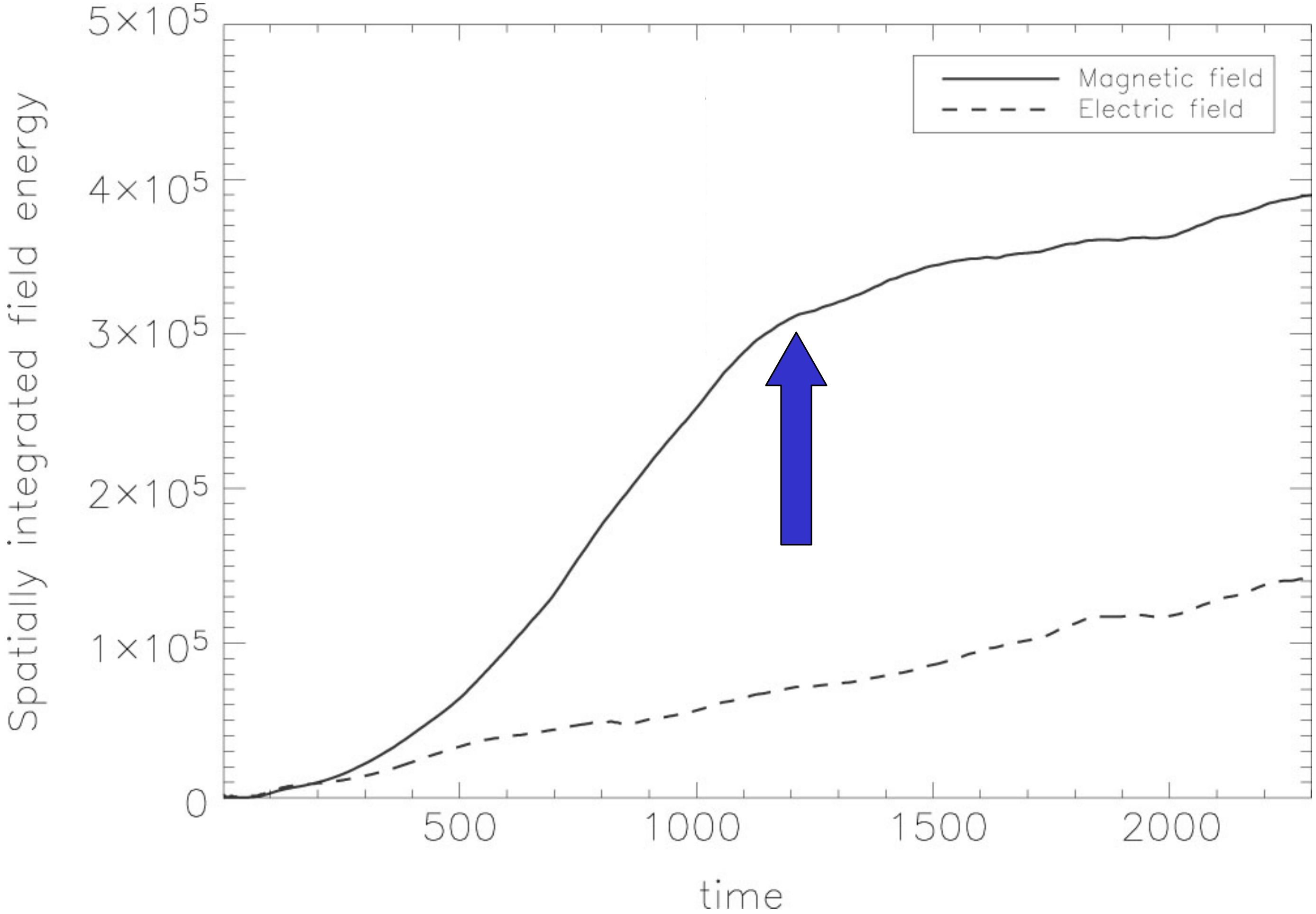
1. Electrons goes through the Weibel instability.
2. Ions deflects on the B-field seeded by the electrons and goes through the Weibel instability.
3. Debye-shielded ion currents continuously merge to larger scale.

Electromagnetic Scale Growth

Fourier spectrum of **B**

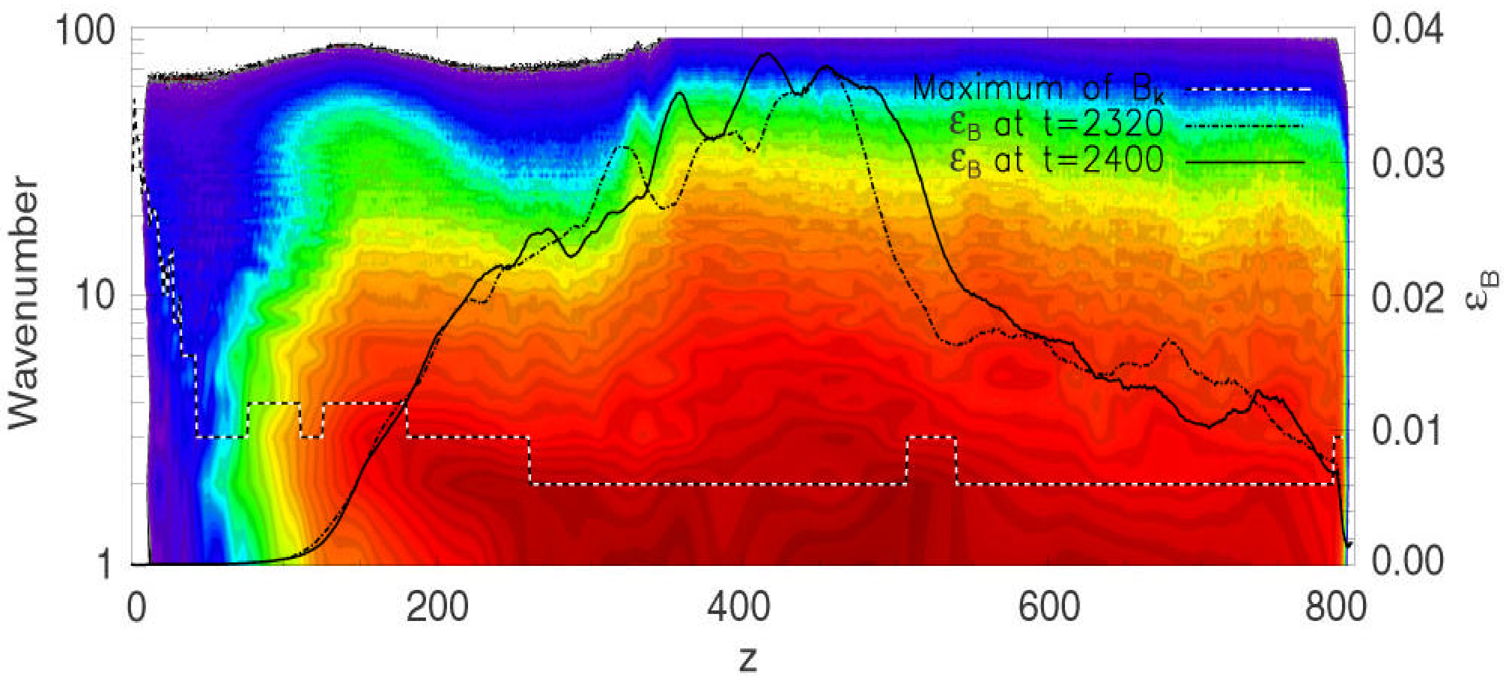


Electromagnetic Energy Growth



Field Generation Efficiency.

$$e_B \equiv \frac{E_{Magnetic}}{E_{Kinetic}} \sim 10^{-3} - 10^{-1} \text{ (observations)}$$



- Simulations consistent with observations!

Disagreement with Observations?

- Normal assumption that the magnetic field remains steady throughout the shocked region.

  Rossi & Rees, astro-ph/0204406

ABSTRACT
In models for gamma ray burst afterglows, it is normally assumed that the external shock strongly amplifies the magnetic field and that this field maintains a steady value throughout the shocked region. We discuss the effects of modifying this (probably simplistic) assumption. The observations are incompatible with a post-shock field that decays too rapidly. However if the field pervaded only a few percent of the total thickness of the shocked shell (and the electrons undergo only inverse Compton losses in the remainder) the models would be more compatible with the high external densities expected in star-forming regions. Afterglow observations in all wavebands, especially at radio wavelengths, could help to pin down the field structure.

- Some level of polarization is seen in afterglows. Is a highly tangled magnetic in contrast with this?

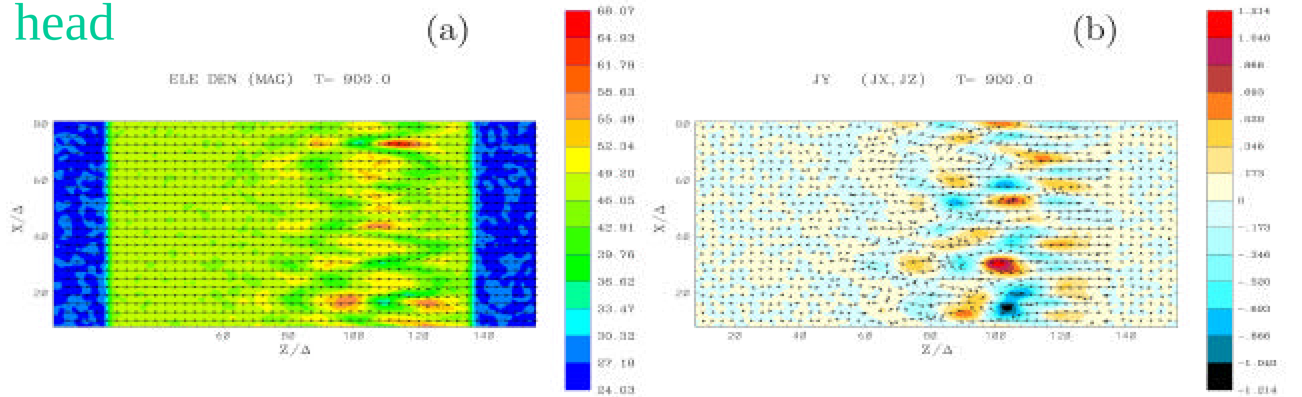
  Not if the jet is seen off-axis.

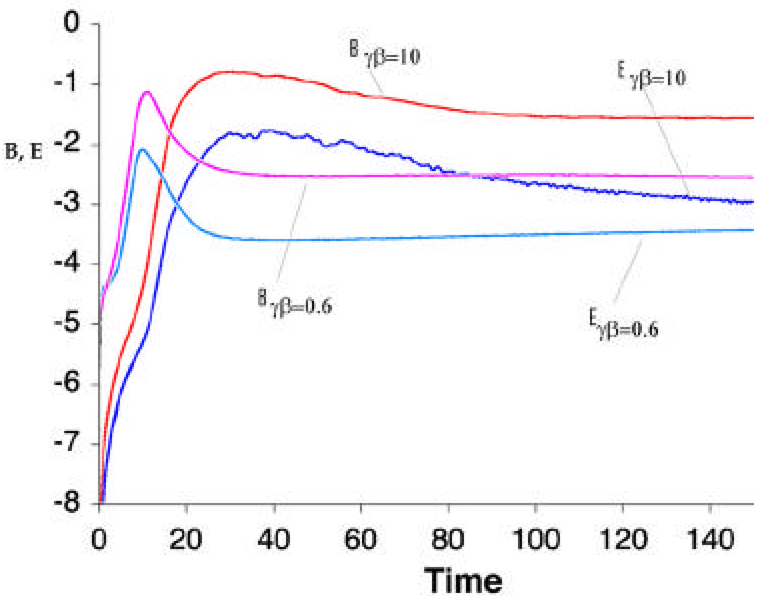
  Sari 1999; Ghisellini & Lazzati 1999; Medvedev & Loeb 1999;
  Granot et al. 2002; Rossi et al. 2002

Other PIC Players

K.-I. Nishikawa, P. Hardee, G. Richardson, R. Preece, H. Sol, G. J. Fishman

85 x 85 x 160 – jet head





Silva et al 2003

e^+e^- plasma.

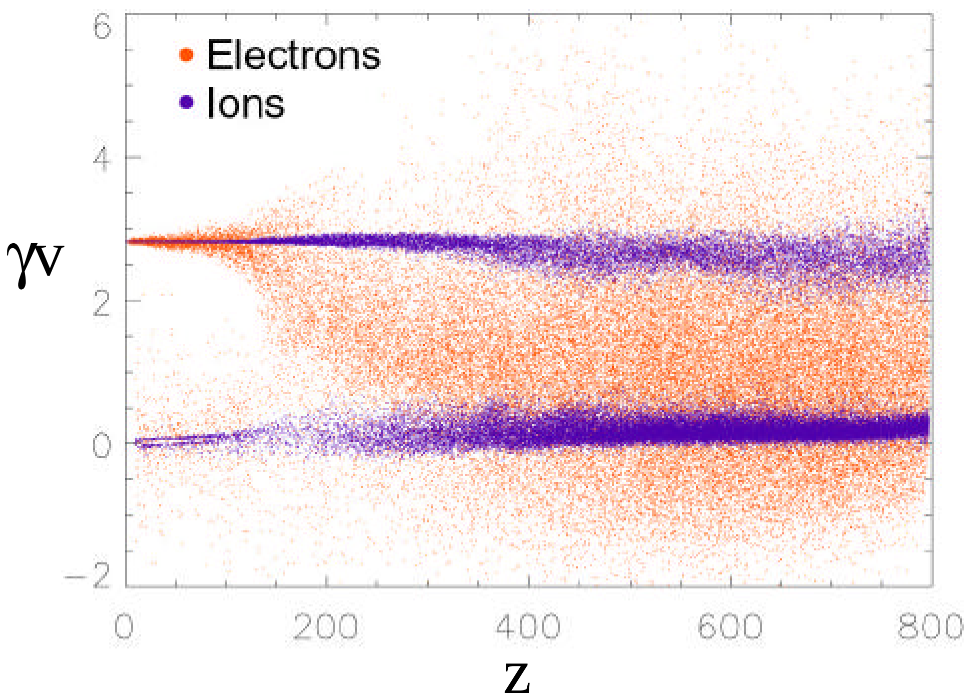
Particle Acceleration

Acceleration Mechanisme

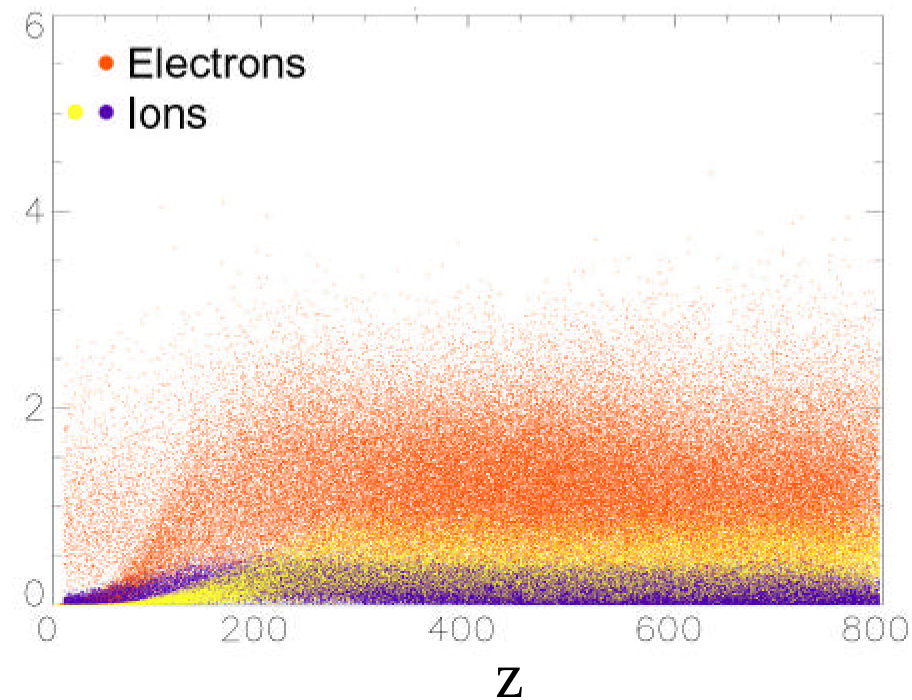
- The generated (highly tangled) magnetic field isotropizes the velocity distribution.
- The Weibel mechanism also creates charge separation which gives an electrical field that accelerates the particles.

Particle Acceleration

Longitudinal acceleration



Transverse acceleration

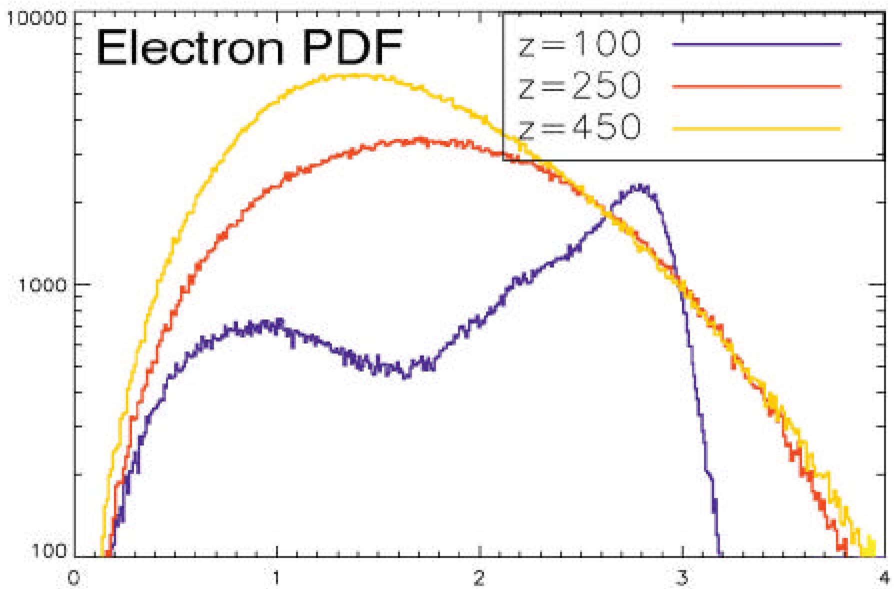


Particle Velocity Distributions

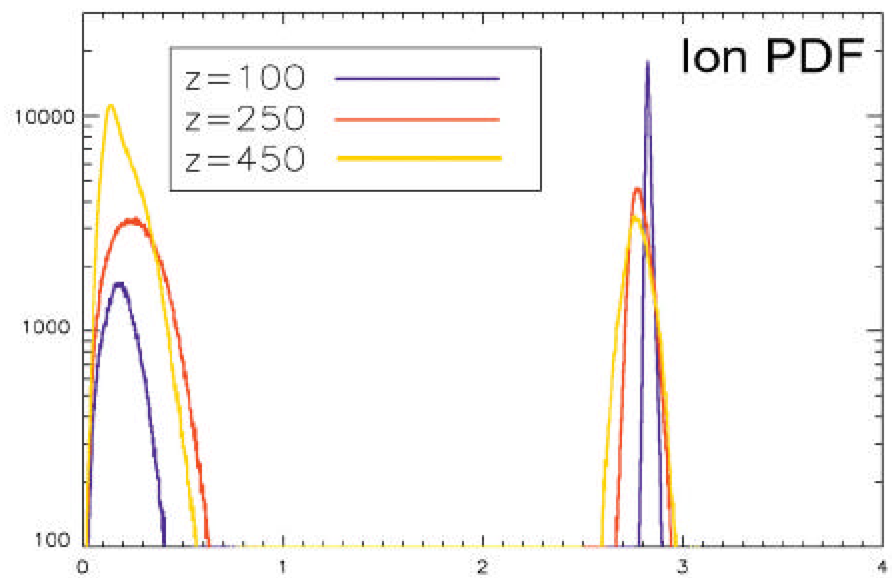
Electrons

Ions

N

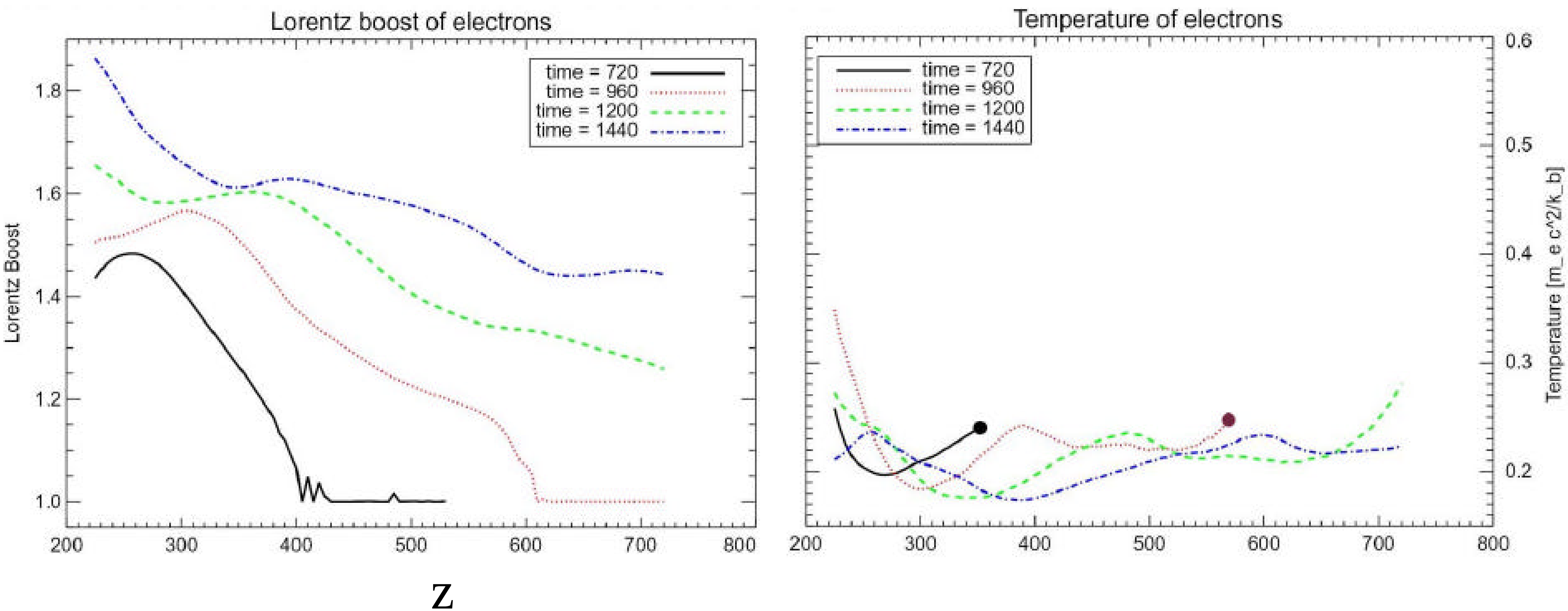


γv



γv

Shock Jump Conditions



Should eventually converge towards jump-conditions.

Conclusions

Particle Acceleration

- The electrons are effectively thermalized in the shock and that the temperature converge very fast.

- We see no sign of a non-thermal tail (could be found at higher Γ).
  (Ellison & Double, 2002)

- We have seen that particle acceleration and magnetic field generation are two sides of the same story.

Magnetic field Generation

- The Weibel two-stream instability is able to create a magnetic field strong enough to match observations ($\varepsilon_B \sim 1\%$).
- ε_B and ε_e are very interdependent and not free parameters as assumed.
- The generated magnetic fields coherence scale, range much longer downstream than the expected couple of skin-depths.
- The transverse correlation length is larger than expected from a linear analysis and is, so far, only limited by the box-size.

Future Work

- Investigate particle acceleration at higher Γ to determine if there is a non-thermal tail
(in progress).
- Derive the collisionless shock jump-conditions.
- Everything is ready for synthetic spectra from the simulations.
(in progress).

Have some coffee.
(in progress).